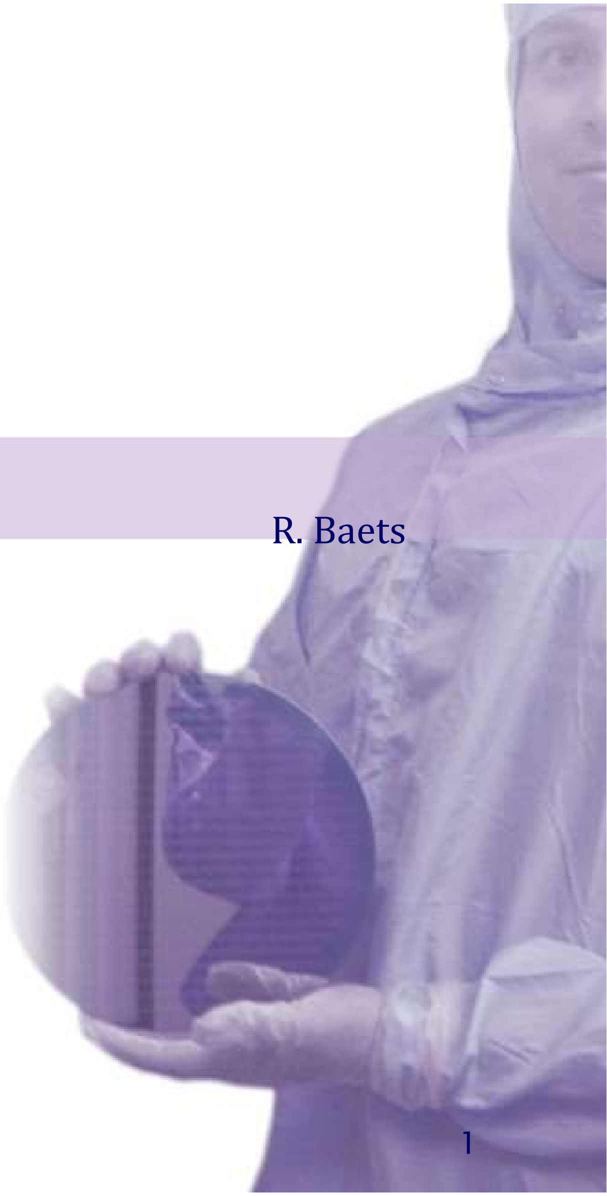
Photonics

R. Baets

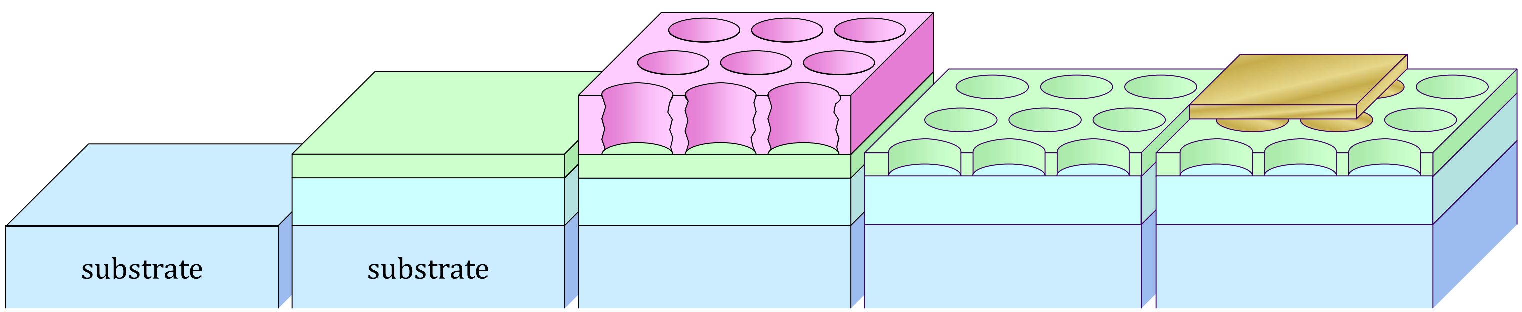
Technology of optoelectronic semiconductor components – Part A

A: Growth and deposition
   Lithography and etching
B: Clean rooms
   Fabrication of the laser diode



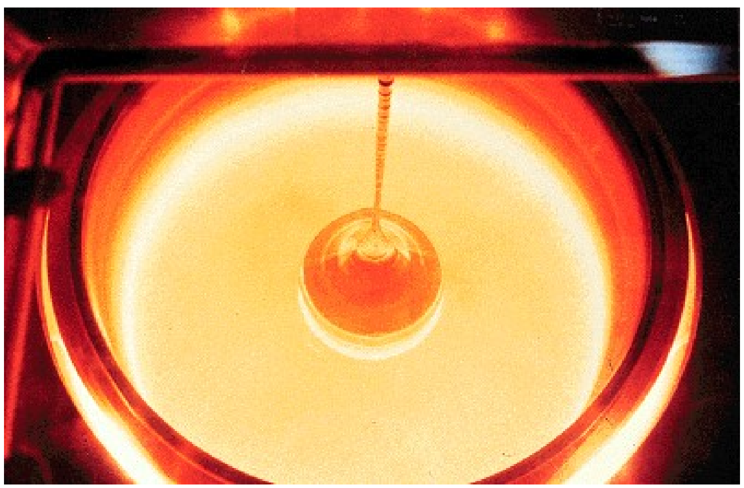
Typical fabrication

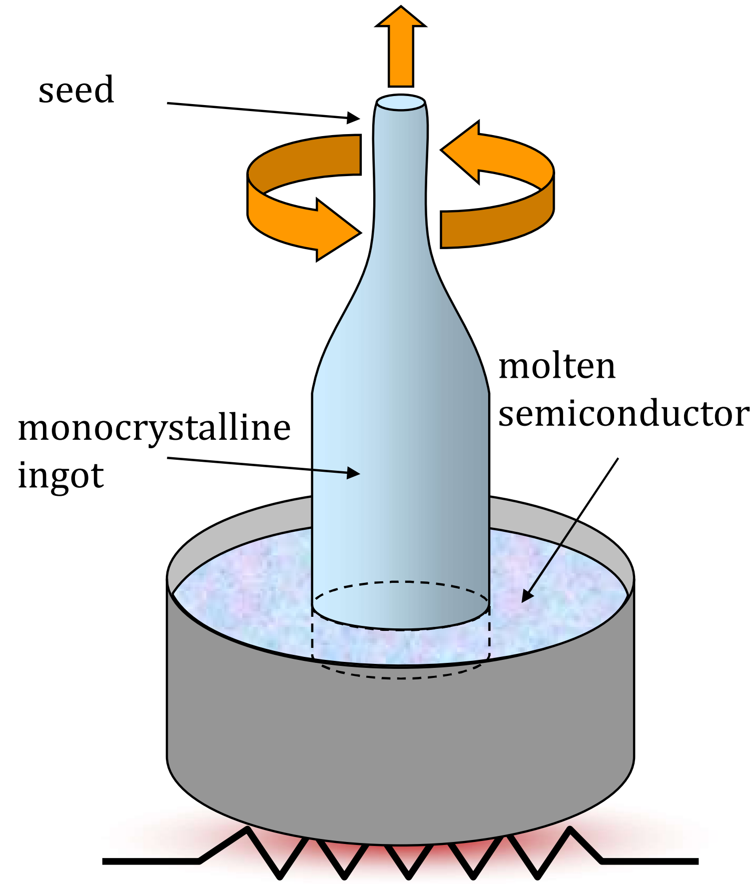
- Clear substrate: mono-crystalline semiconductor material
- Epitaxial growth: mono-crystalline layers of (other) semiconductors are deposited on it
- (Photo)lithography: a pattern is applied to a (light) sensitive resist
- Etching: by means of chemical or plasma process the pattern in the resist is transferred to the semiconductor under it
- Deposition: extra material (semiconductor, isolator, metal) is put on top of the structure
- Metallization: a metal layer (e.g. gold) for electrical contact



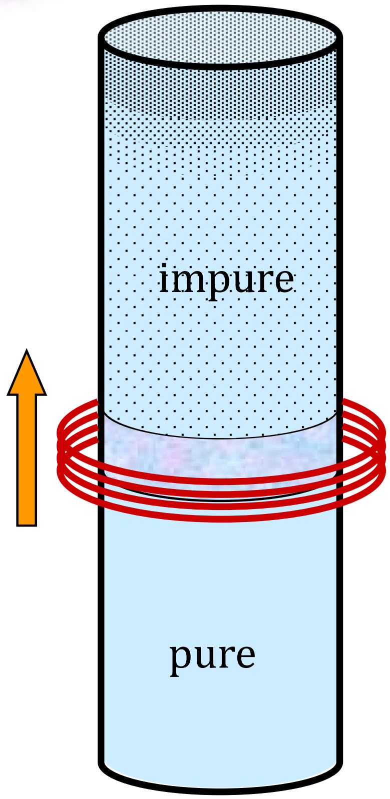
Monocrystalline semiconductor (1)

- Czochralski process:
  an ingot grows from a "seed", which
  is slowly rotated and pulled upwards
  from a bath

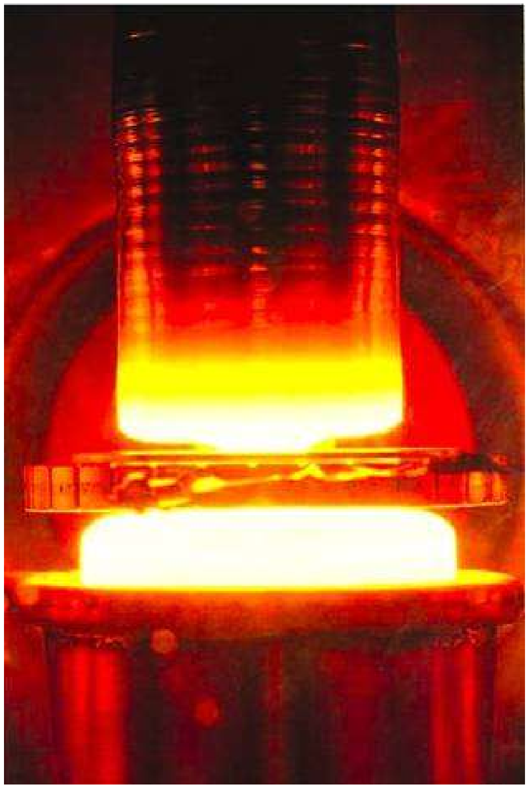




Monocrystalline semiconductor (2)



- Floating zone process: a melted zone moves impurities to the side
- The process is repeated
- Less popular than Czochralski process
  - smaller diameter of the ingot
  - less purity



Monocrystalline semiconductor (3)

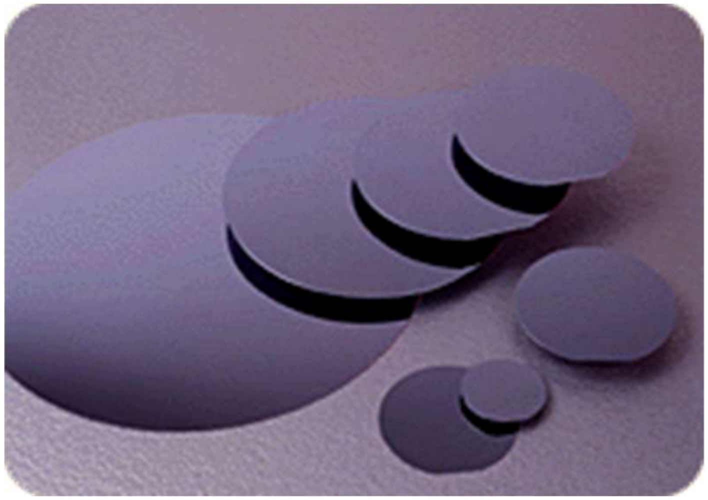
- Result: an ingot
- Diameter: 2” (5cm) → 12” (30cm)
    - depends on the market
(silicon industry: largest boules)
    - depends on the material
(the better the heat conductivity,
the larger diameter can be achieved)

Semiconductor wafers

- An ingot is sliced with a saw
- The wafers are polished

- Diameter: 2” (5cm) → 12” (30cm)
  - depends on the market
  - depends on the material
    - Si: 4” → 12”
    - III-V: 2” → 6”

- Thickness: 400µm → 1mm
  - depends on the diameter (mechanical strength)

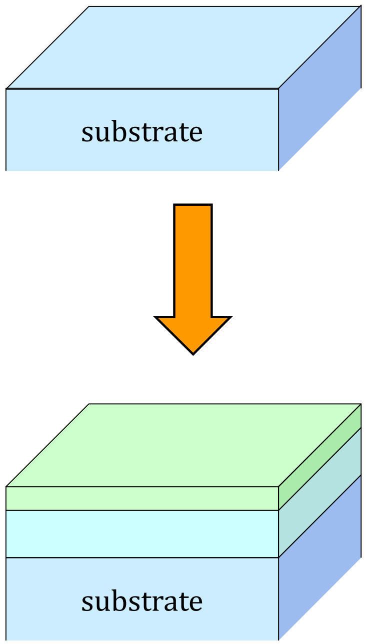


Epitaxial growth (1)

- Wafer = pure material
- Components consist of layers with different doping
  - n or p
  - different concentrations

- Deposition of layers
  - mono-crystalline
  - matched to the crystal structure of the substrate

= epitaxial growth



Epitaxial growth (2)

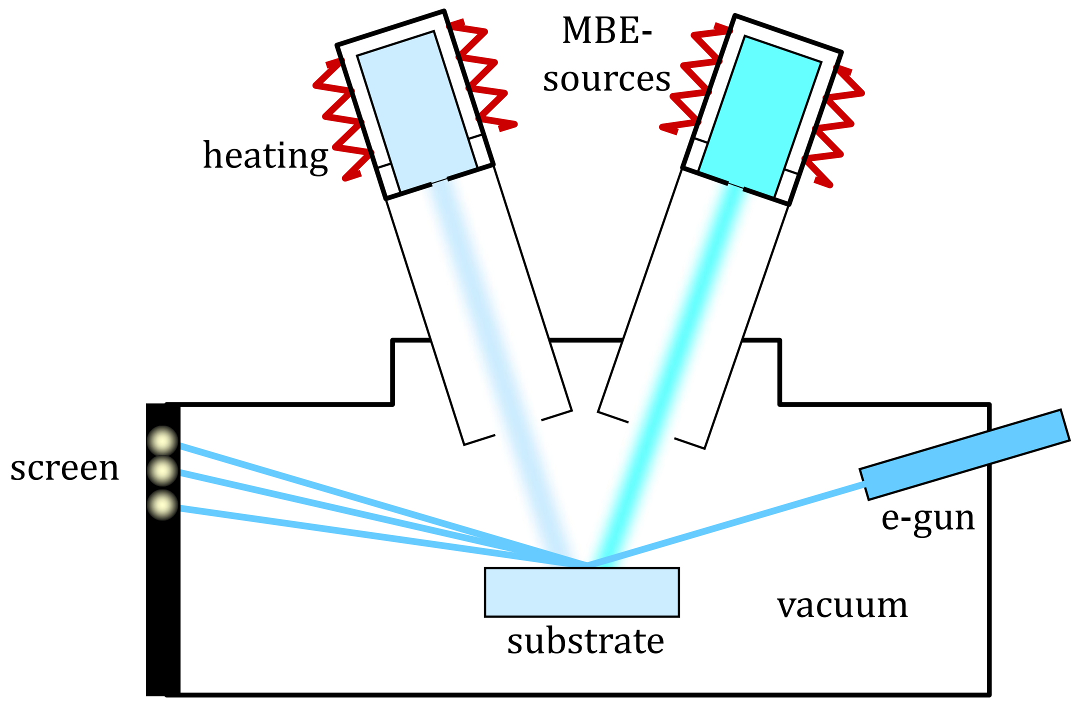
- Deposition of mono-crystalline layers: Atoms bind to the surface
  - Sources deliver material in molecular form
  - Reactions on the surface
  - Remaining substance is removed

- Deposition of materials:
  - with a molecular beam (Molecular Beam Epitaxy: MBE)
  - with a liquid (Liquid Phase Epitaxy: LPE)
  - from gas phase (Vapor Phase Epitaxy: VPE)

    Special case: with metal-organic compounds
    (Metallo-Organic Chemical Vapor Deposition: MOCVD
    or Metallo-Organic Vapor Phase Epitaxy: MOVPE)

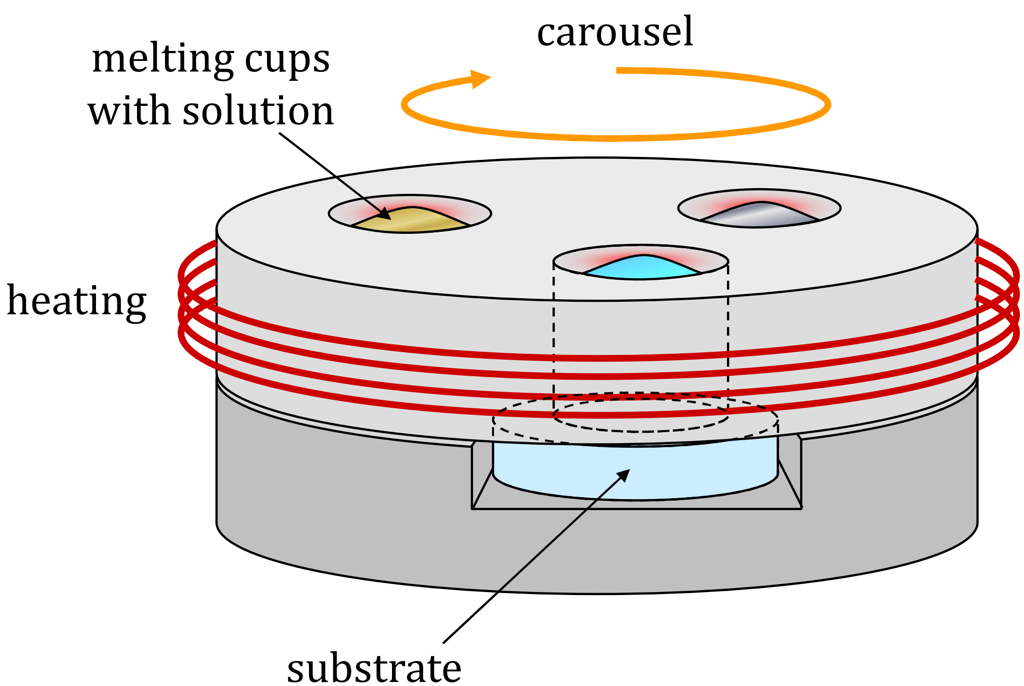
Molecular beam epitaxy

- Growth in an ultra-high vacuum
- Delivery of reagents from different molecular beams (generated by thermal effusion)
- Very good control of the composition
- Very thin layers (1 atom) can be created



Liquid Phase Epitaxy

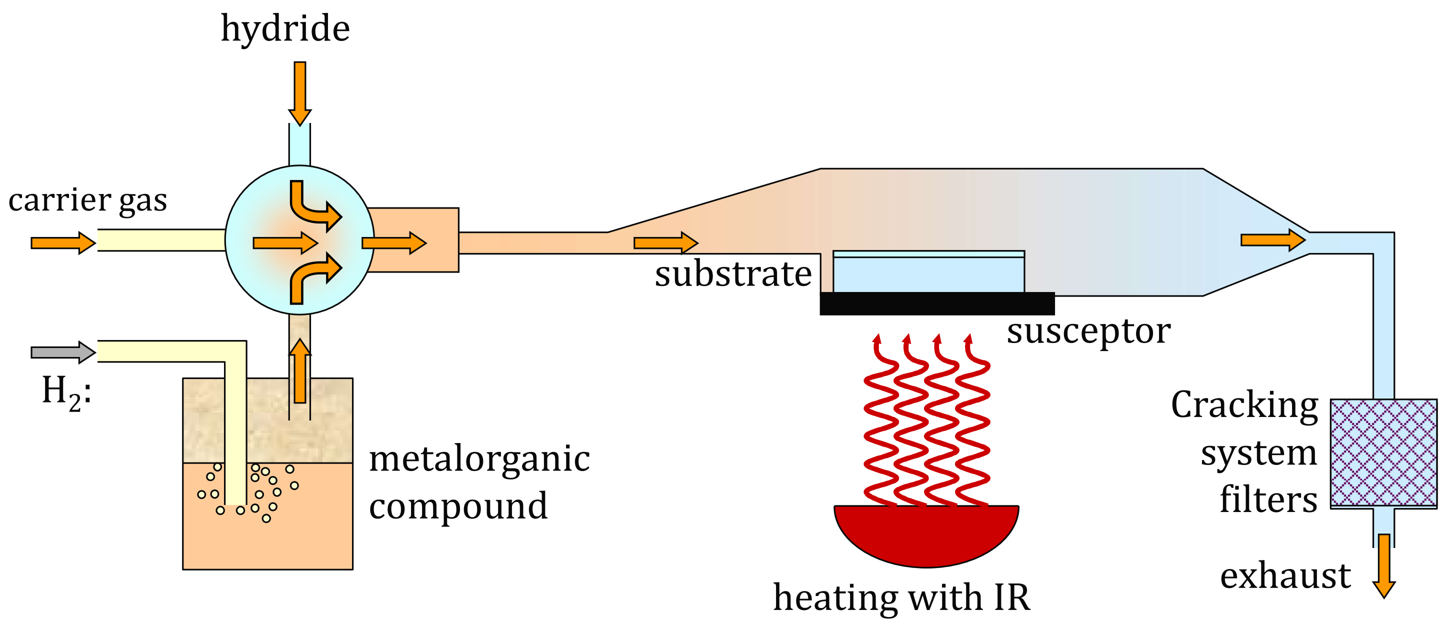
- Material: group V material diluted in a molten group III material
- Solvent is cooled in contact with substrate: saturation
- Nucleation of III-V material on the substrate



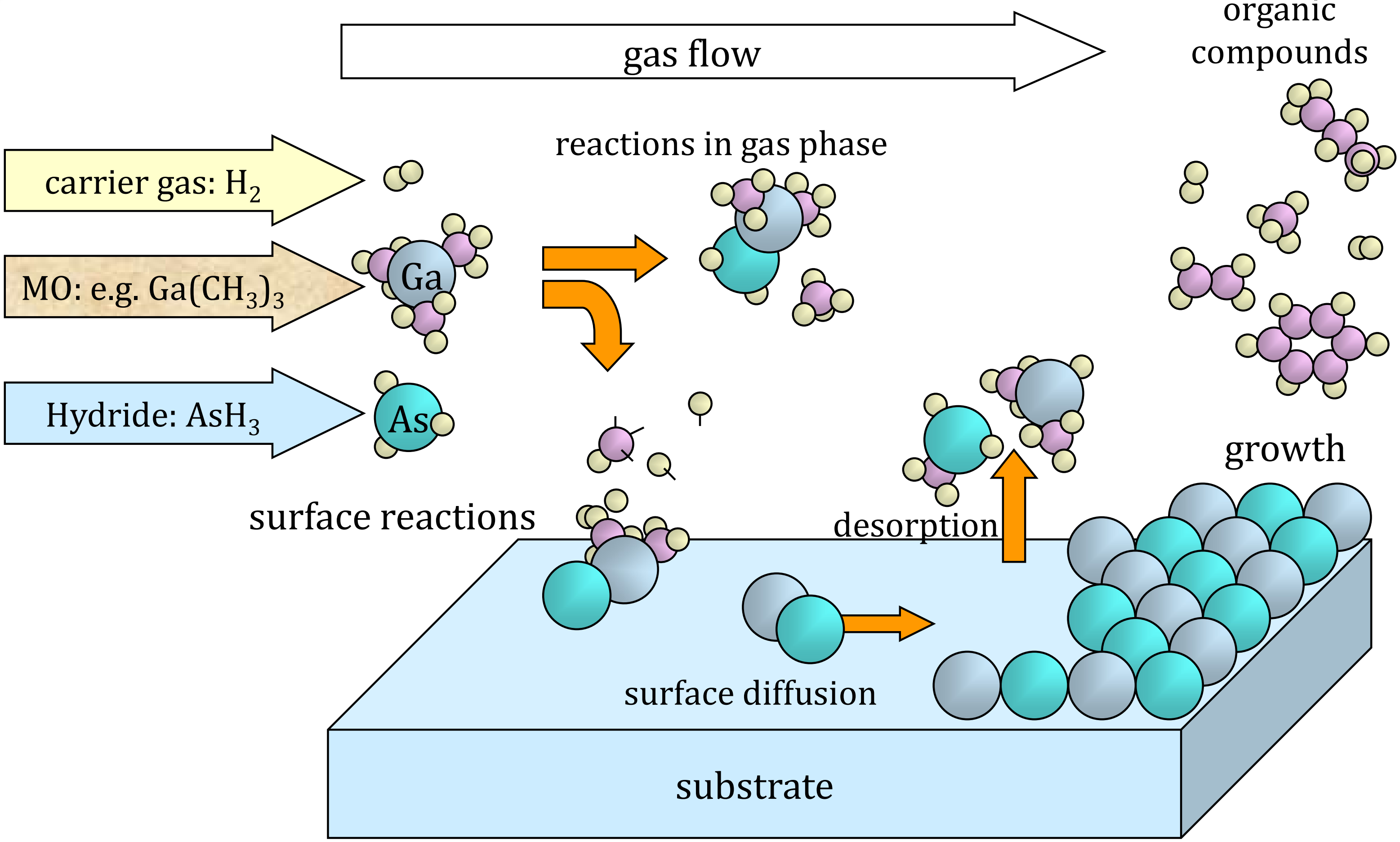
- Not used much any more

MOCVD of III-V materials (1)

- Materials
  - Metalorganic compounds (group III)
  - Hydrides (group V)

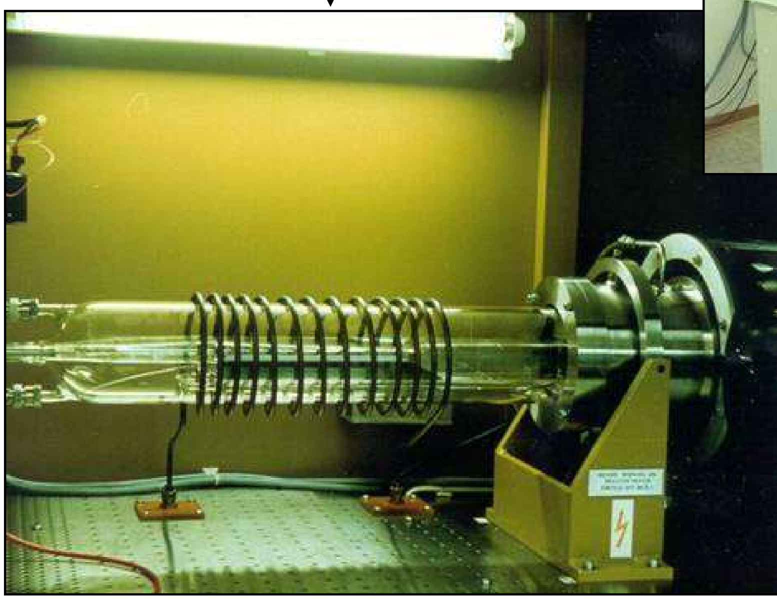


MOCVD of III-V materials (2)



MOCVD (MOVPE)

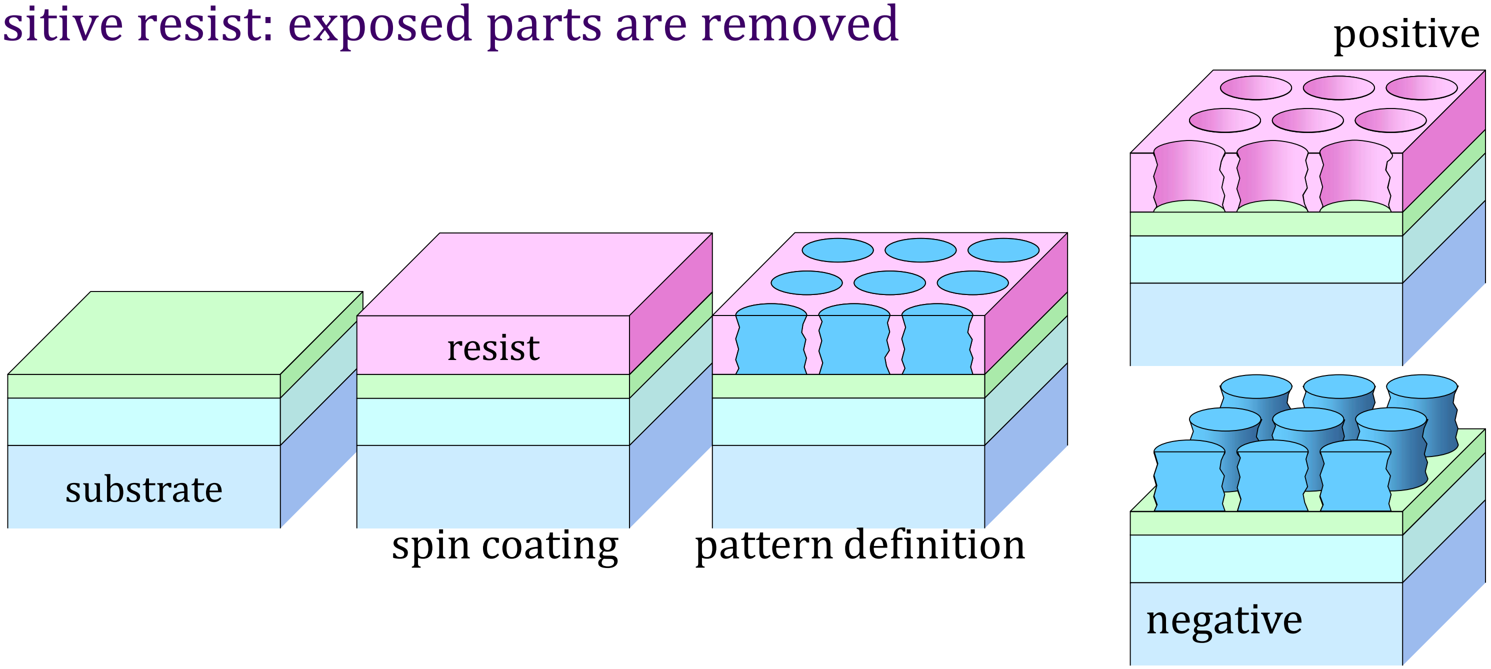
simple instrument
limited possibilities



complex instrument, more safe
greater possibilities
(more layers)

Lithographic methods

- Lithography
  - A pattern is first defined in a sensitive resist (lithography)
  - Negative resist: exposed parts remain
  - Positive resist: exposed parts are removed



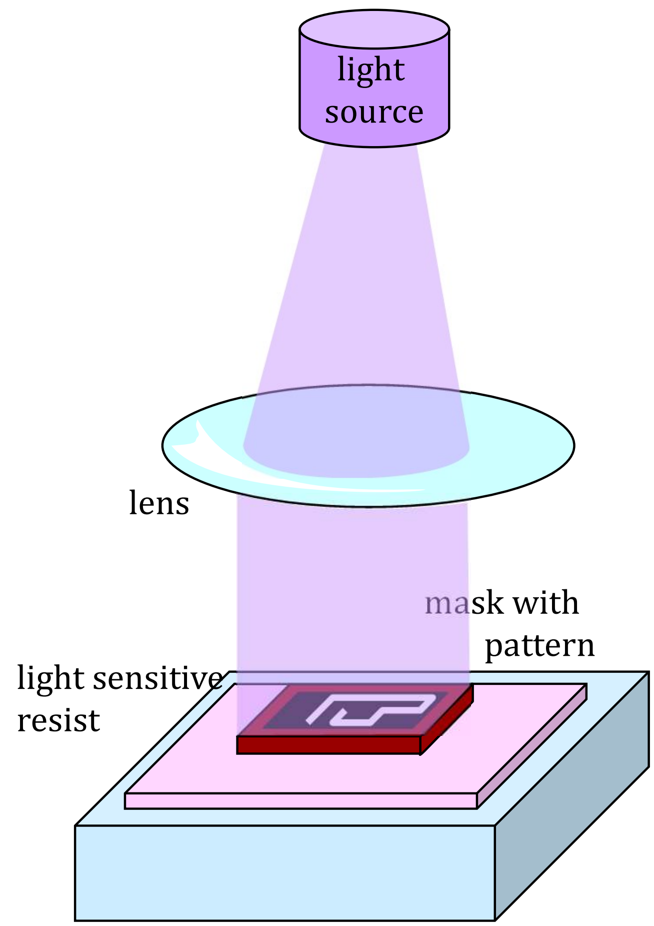
Contact photolithography

- A pattern is defined in a UV-sensitive resist
- Mask is aligned and attached to the resist
- Illumination with a uniform UV beam (e.g. mercury lamp)

- Advantages:
  - Simple process
- Disadvantages:
  - Alignment is difficult
  - Limited resolution

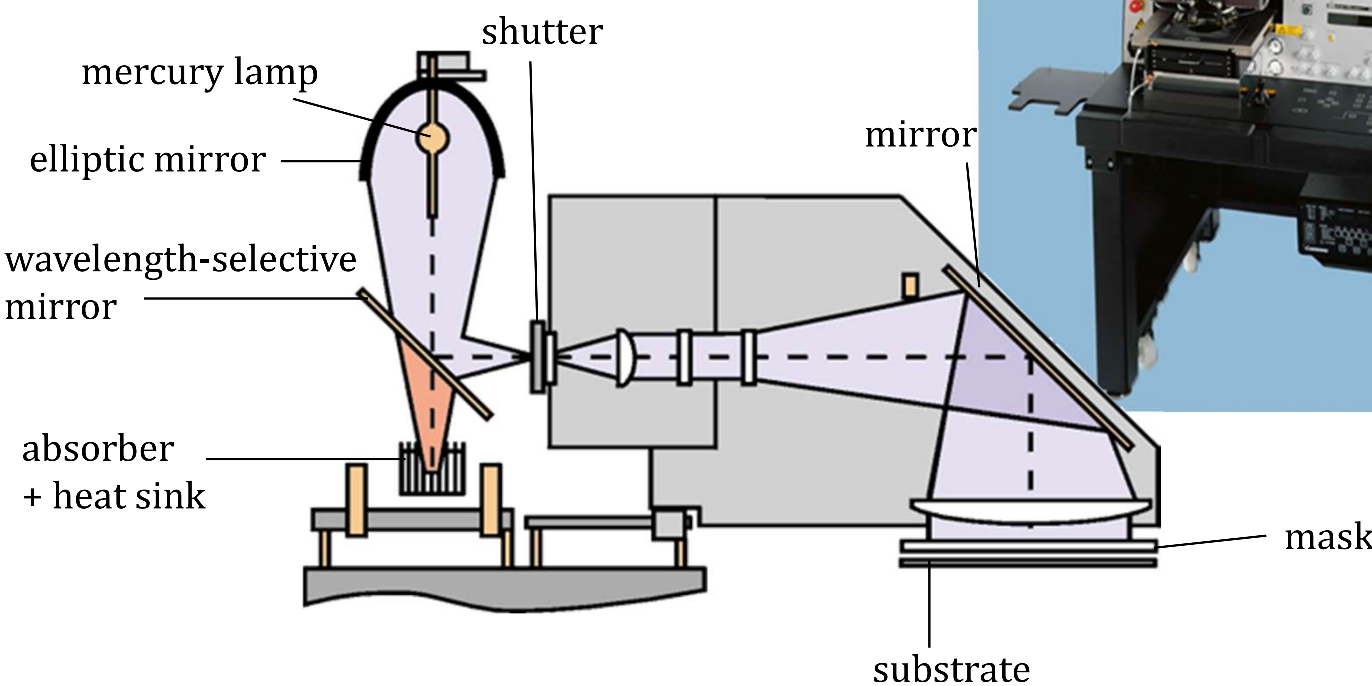
$$W \sim \sqrt{\lambda g}$$

λ: light wavelength
g: distance between mask and lower resist surface



Contact lithography

- SUSS MicroTec MA6/MA8



Projection lithography

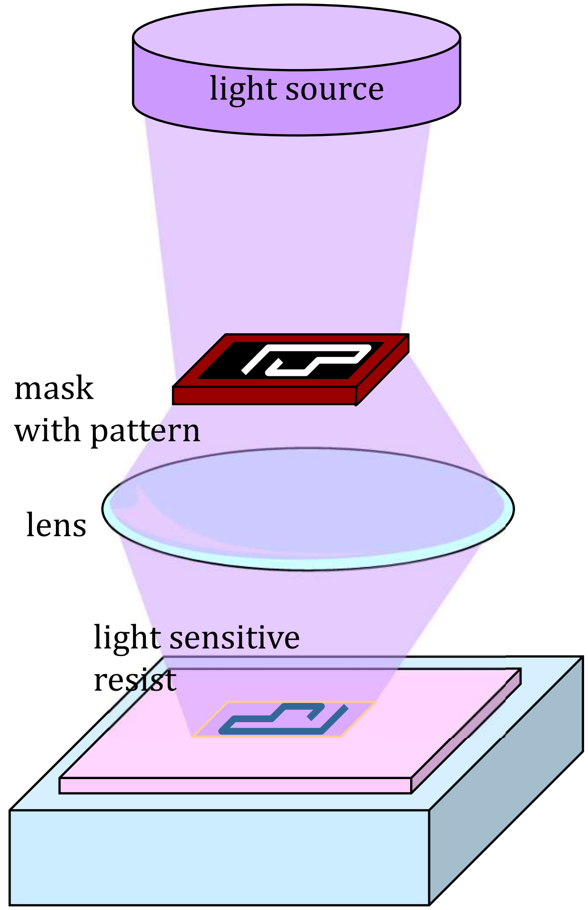
- Mask pattern is projected on the resist

- Advantages:
  - Pattern is copied across the wafer
  - Use of reducing optics
    (mask pattern is larger than chip)
  - Applicable in industry (CMOS)

- Disadvantages:
  - Expensive equipment
  - Limited resolution (~wavelength)

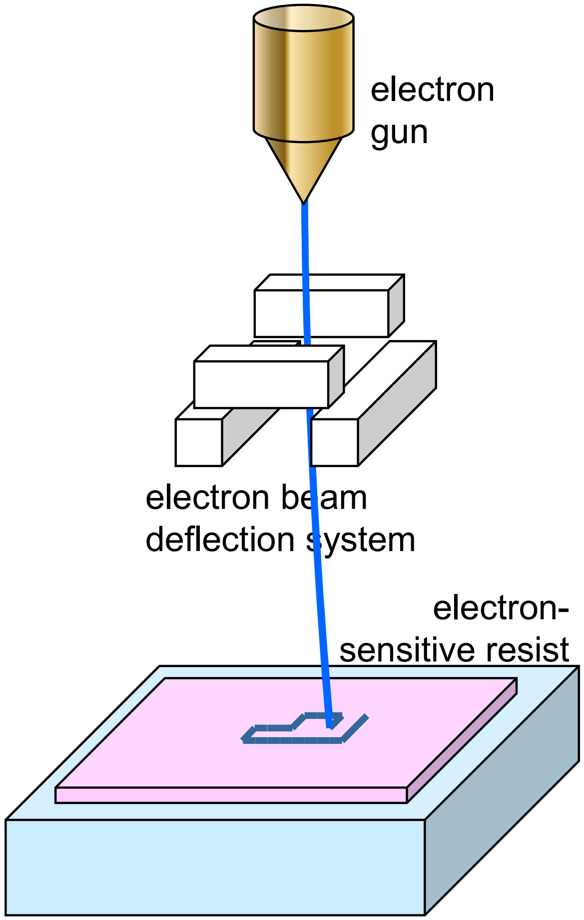
$$W \sim \frac{\lambda}{NA}$$

λ: light wavelength
NA: numerical aperture of a lens



E-beam lithography

- Pattern is written directly in the resist with an electron beam
- Advantage:
  - Very high resolution (electrons have very small "wavelength") (nm scale)
  - No mask required
- Disadvantages:
  - (very) Slow
  - Limited area possible without moving sample

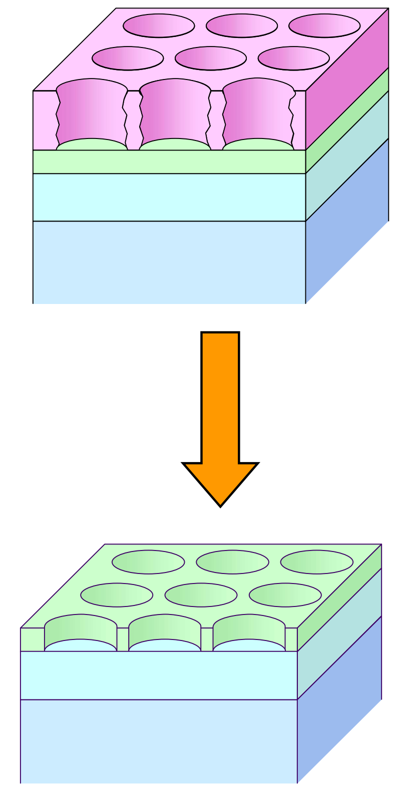


Etching

- Transfer of the pattern in the photoresist to the substrate

- Photoresist serves as a mask during
  - chemical dissolution of the substrate with a reactive liquid
    = WET ETCHING

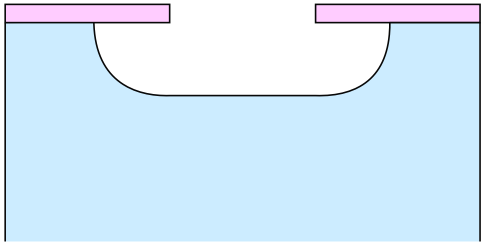
  - chemical dissolution + physical sputtering of the substrate with an energetic plasma
    = DRY ETCHING



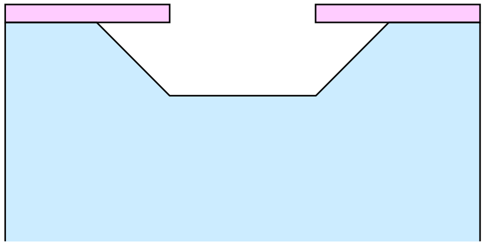
Wet etching of GaAs

- Etchants: $H_2SO_4/H_2O_2/H_2O$
  - H_2O_2 oxidizes the surface
  - H_2SO_4 dissolves the oxide

- Competition between the processes
  - Diffusion-limited: dissolving and removal of the oxide is the slowest: circular profile
  - Reaction-limited: oxidation is the slowest: all oxidized material is immediately dissolved: profile along the most slowly etched crystal plane. (111) in GaAs



diffusion-limited



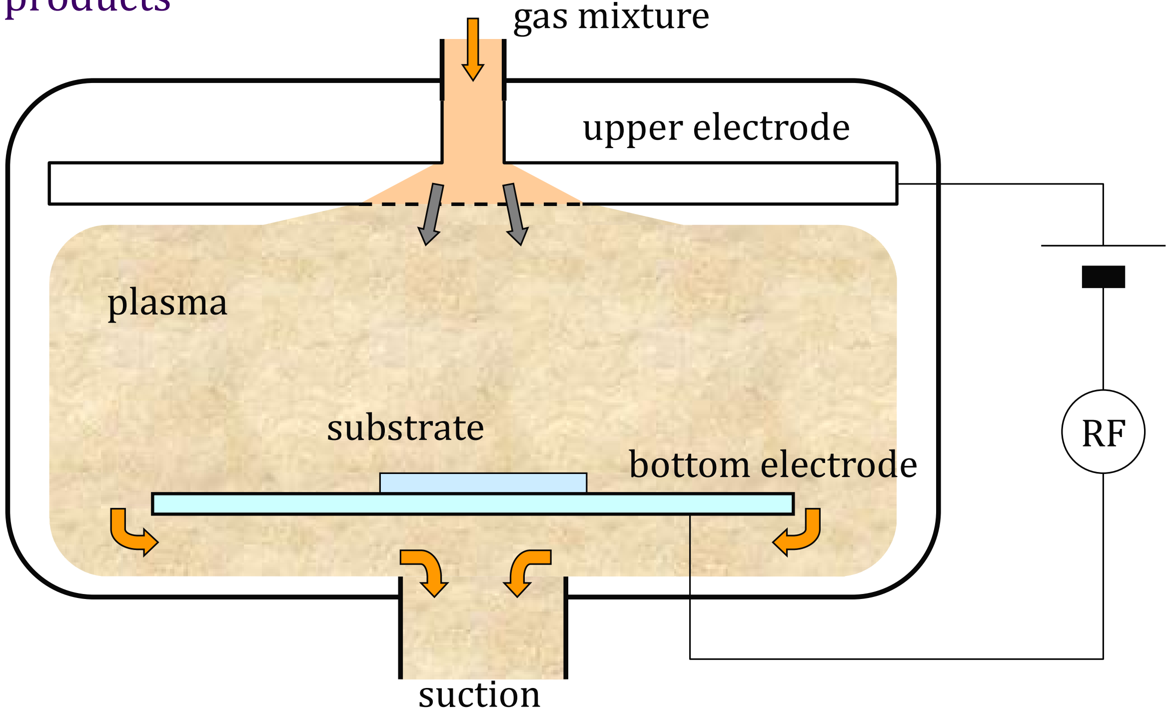
reaction-limited

Plasma deposition

- Electrical isolation / hard masking: SiO_2 or Si_3N_4 or oxynitrides
- Deposition: Plasma-Enhanced Chemical Vapor Deposition (PECVD)
  - Gas mixture is ionized
    - SiH_4/ NH_3 / N_2 for Si_3N_4
    - SiH_4/ N_2O for SiO_2
  - Reaction of radicals and ions on the surface creates a uniform film with required composition
- Advantages
  - Low reaction temperature (use of strong radicals)
  - omni-directional

Plasma deposition

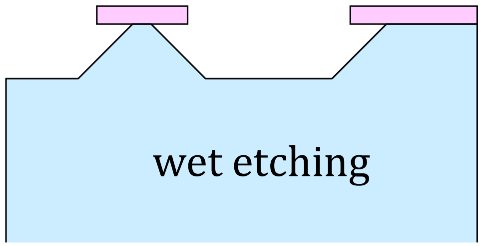
- Gas mixture under low pressure
- Ionization of the gas mixture by RF-voltage
- Removal of the rest products

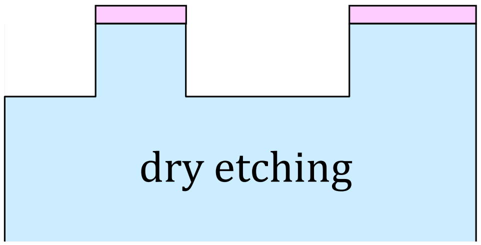


Plasma etching (dry etching)

- Comparable with plasma deposition
  - Gas mixture corrodes substrate instead of depositing
  - Gas mixture can be selective for certain materials

- 'Physical' etching: together with chemical reaction the ions can destroy substrate 'kinetically' by the impact at high velocity:
  - etching in vertical direction
  - no underetching

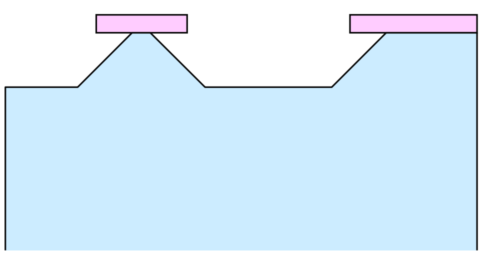




Wet vs. dry etching

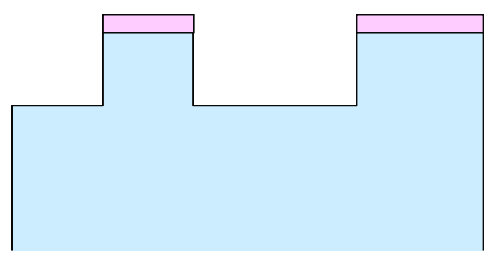
Wet etching

- Advantages:
  - Cheap/Easy process
  - Can be very selective
- Disadvantages:
  - Etches along the crystal plane
  - Underetching
  - Etch speed depends on the mask opening
  - Difficult to make deep, small structures



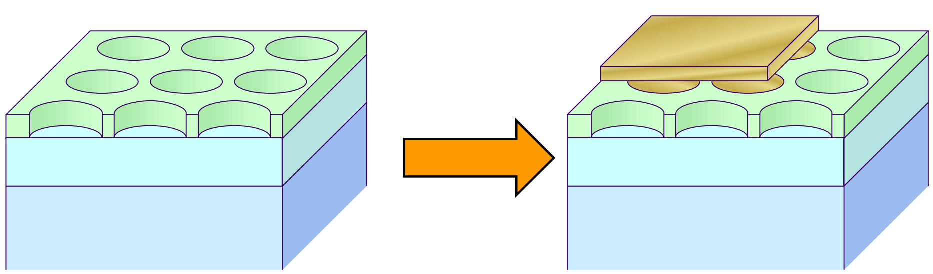
Dry etching

- Advantages:
  - No underetching
  - Possible to make deep, small structures
- Disadvantages:
  - Complex
  - Expensive



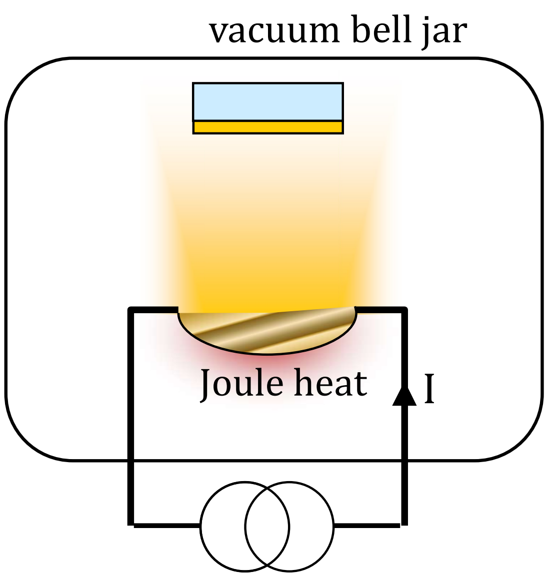
Metallization

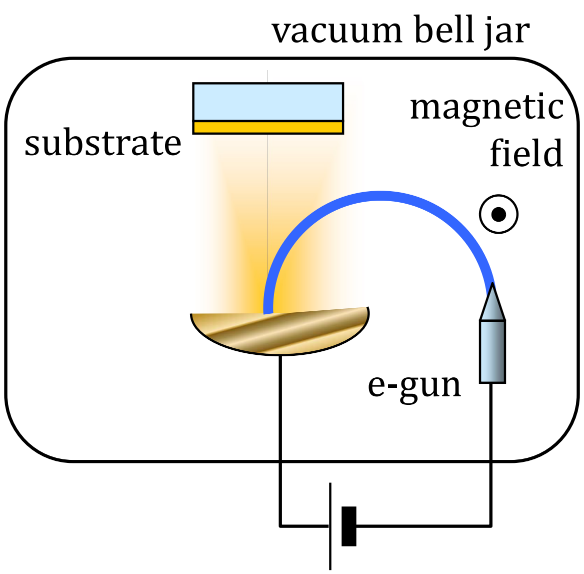
- Goal: electrical connection of the components
- Deposition of metal:
  - thermal evaporation
  - sputtering
- Pattern definition in metal
  - Lithography + Etching
  - Lithography + Lift-off



Thermal evaporation

- Joule evaporator
  - Heating by high electrical current through the crucible with metal
  - Limited in temperature
- Electron beam evaporator
  - Heating by the high-energy electron beam
  - Very high temperature

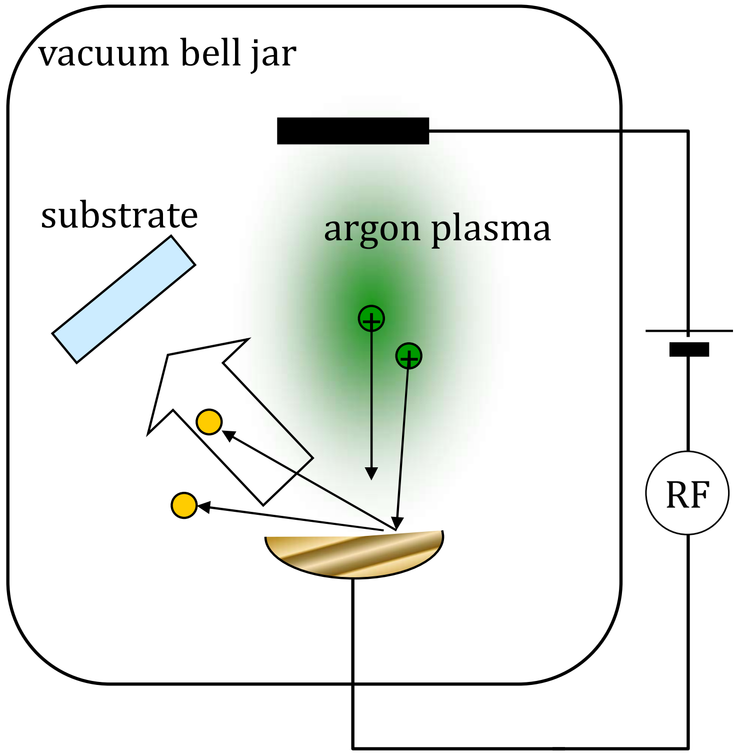




Sputtering

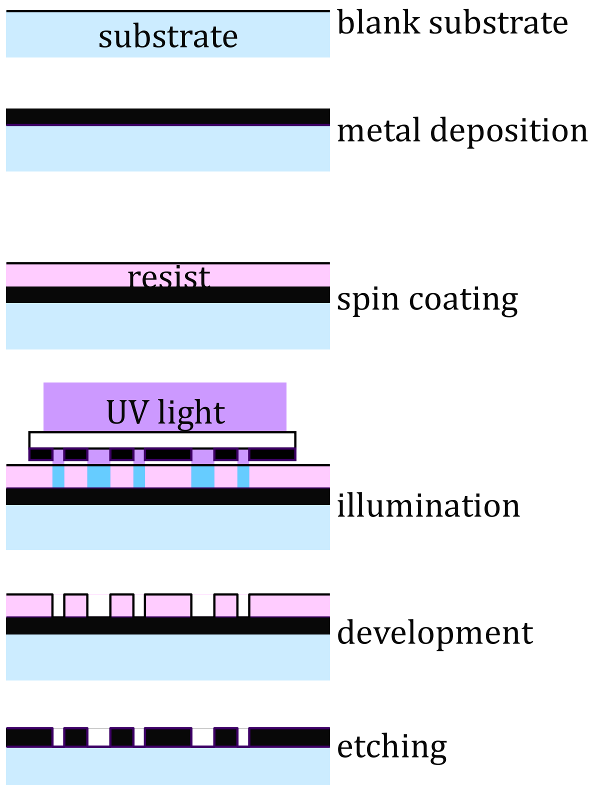
- Kinetic 'dislodging' of the material
  - Argon is ionized
  - Ions are accelerated
  - Released particles are deposited on the substrate and the walls

- Possible for materials with high melting temperature (e.g. tungsten)
- Less precise control

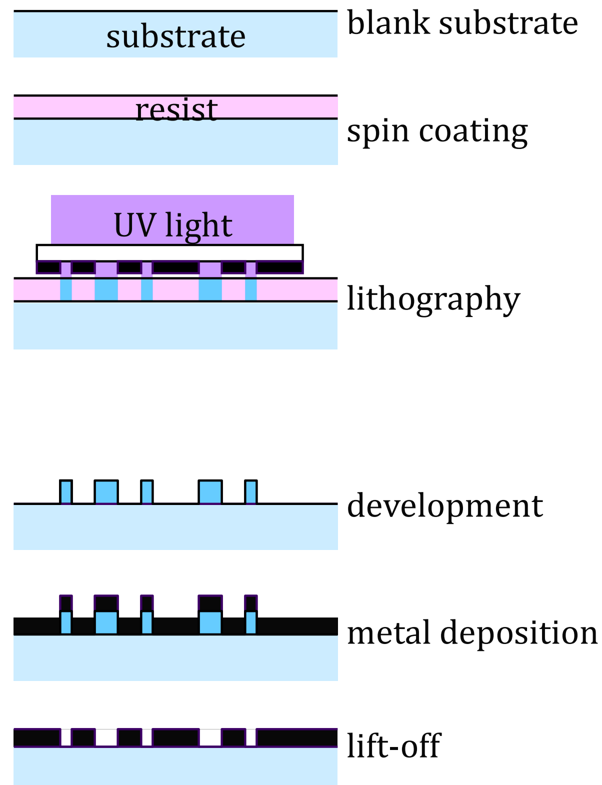


Fabrication by etching and by lift-off

- Fabrication by etching



- Fabrication by lift-off



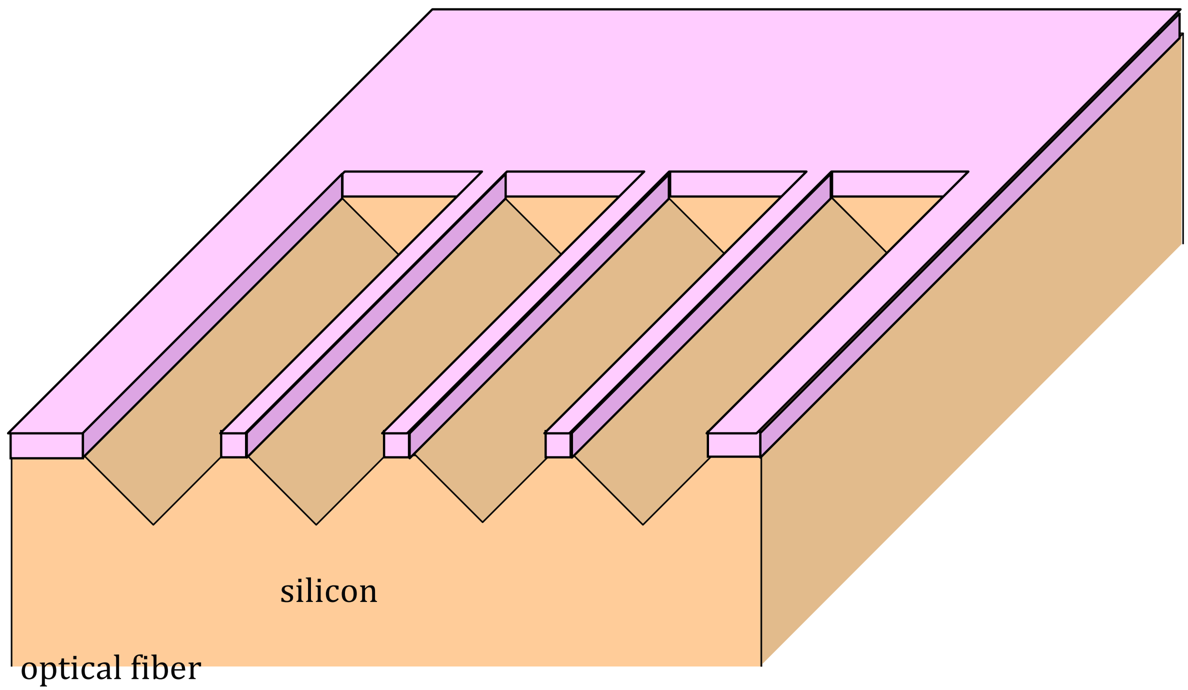
Packaging

- Electrical chips
  - die bonding: chip in protective package
  - wire bonding: wiring to external circuit
  - tolerant in positioning
  - package serves as a heat sink

- Photonic chips
  - Critical alignment with fibers (< 100nm positioning)
  - Very good temperature control is required (refractive index ~ temperature)
  - Can reach 60% of the cost price

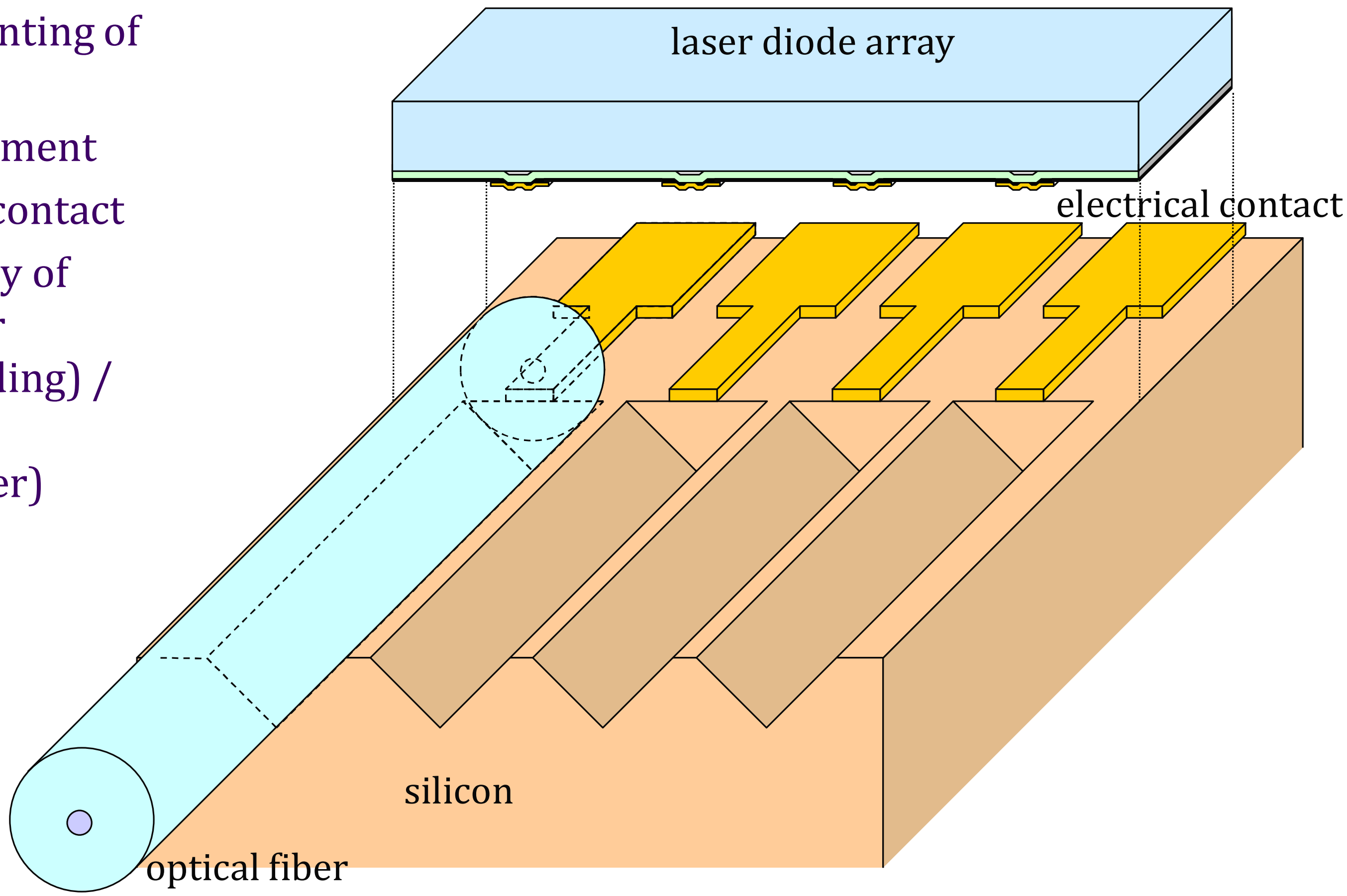
V-grooves for alignment

- Wet etching of V-grooves in Silicon along (111) plane
- Depth of the grooves is precisely controlled

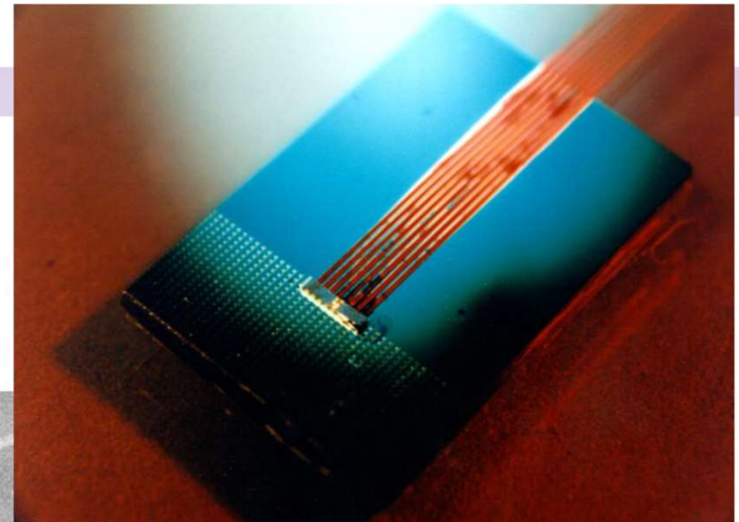


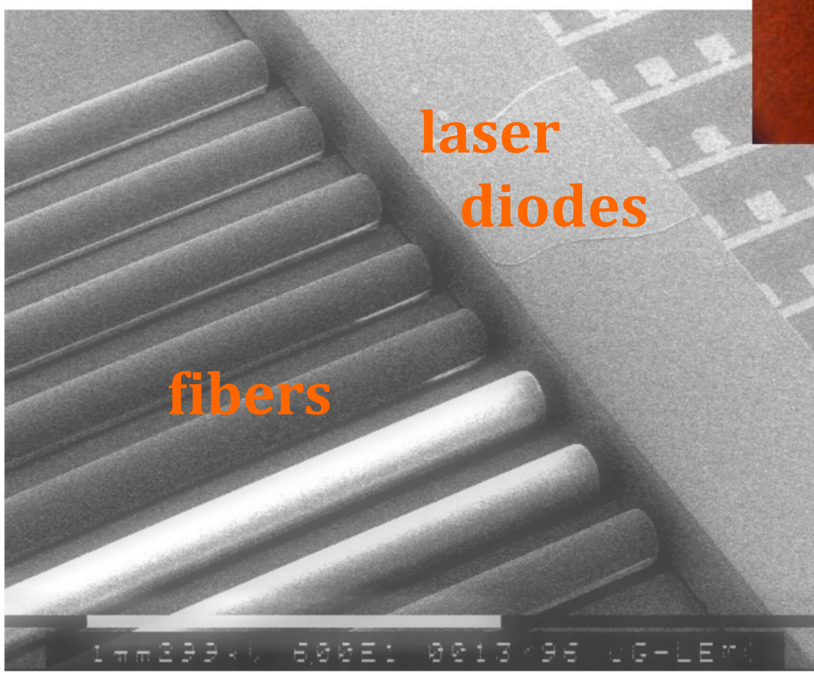
V-grooves for alignment

- Flip-chip mounting of laser diodes:
  - good alignment
  - electrical contact
- Limit: accuracy of fiber diameter (125 µm cladding) / core position (9 µm diameter)



V-grooves





Photonics

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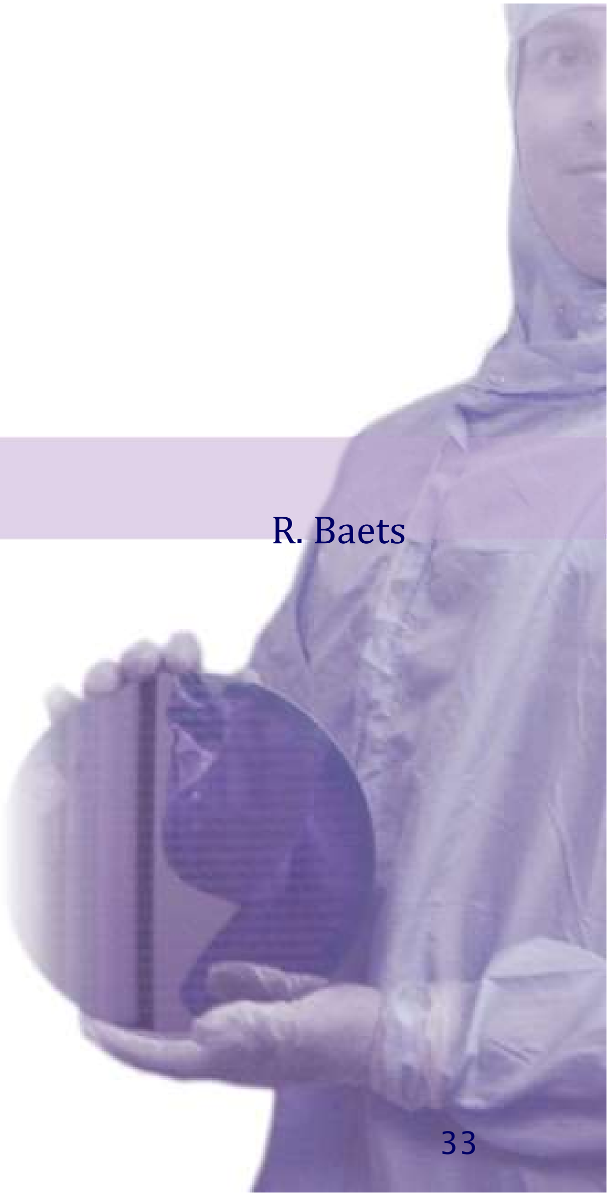
Technology of optoelectronic semiconductor components – Part B

Clean rooms

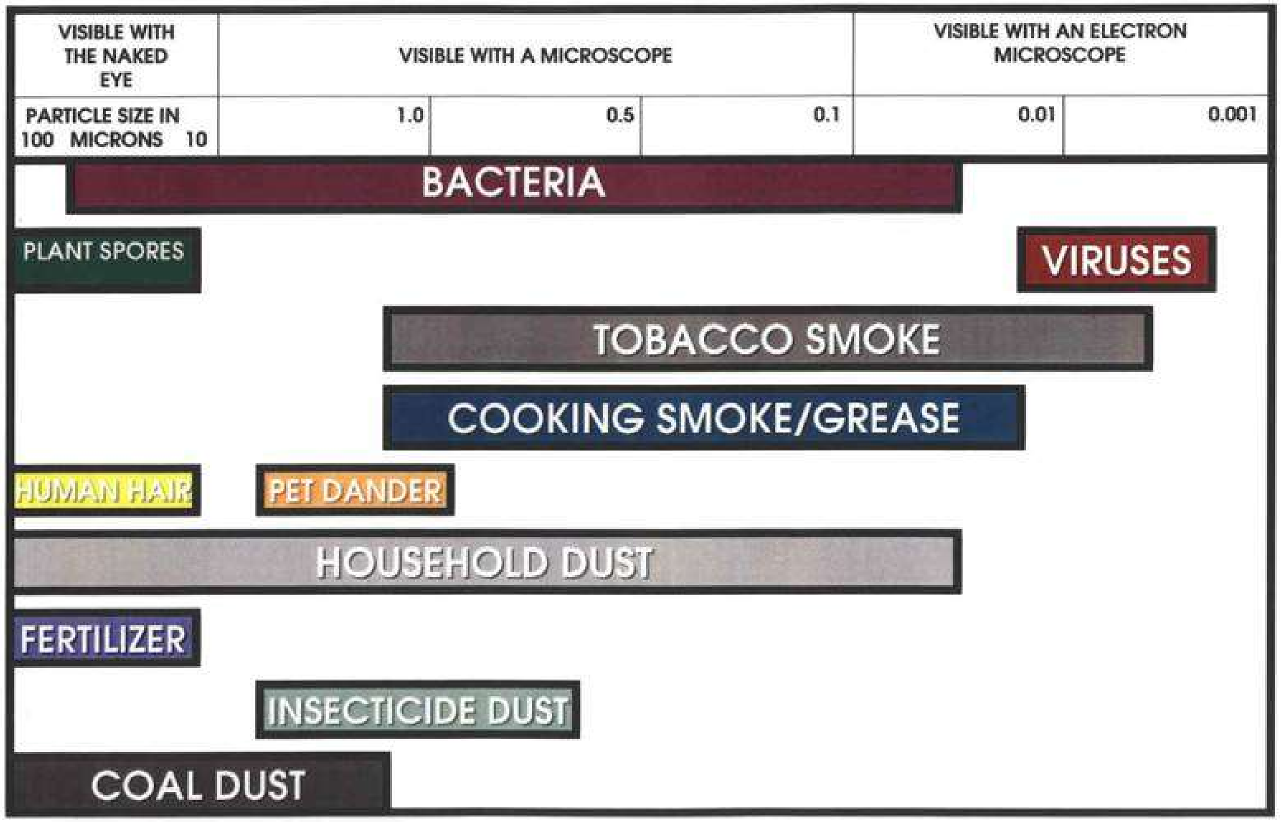
Fabrication of the laser diode



Clean rooms

- Fabrication of semiconductor components:
  - Stable environment:
    - temperature is accurate to 0.5 °C
    - humidity approx. 30° +/-0.5 °
  - Clean-room standardization
    - Classification according to the number of dust particles per cubic feet: Class 1 .. 10 .. 100 ……
- Solution
  - Keep dust outside: lock
  - Do not generate dust: special packaging
  - Do not collect dust: no unnecessary horizontal surfaces and corners
  - Dust removal: air circulation

Types of dust

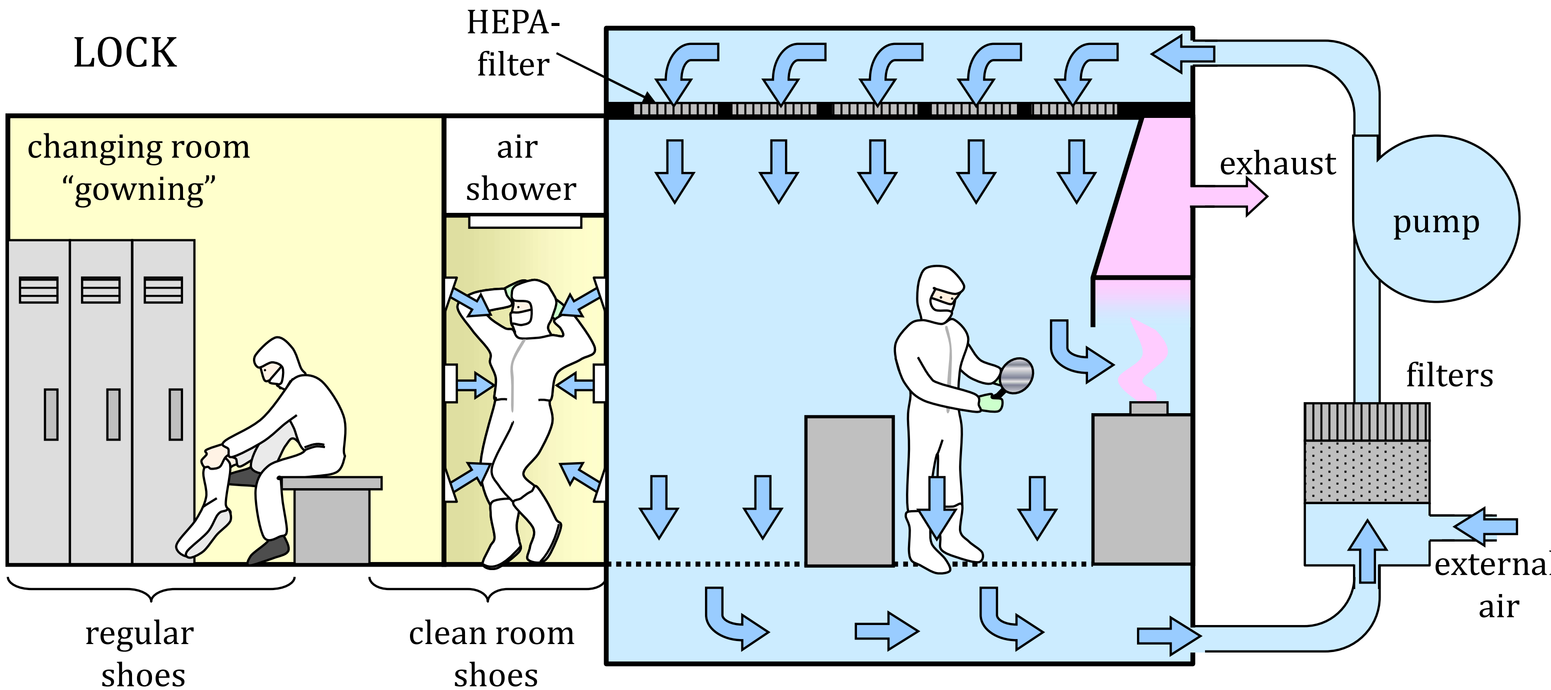


Generation of dust by people

- Generation of dust >0.3μm per minute by one person
  - Sitting or standing: 100,000
  - Nudging head or a hand: 500,000
  - Nudging body: 1,000,000
  - Standing up: 2,500,000
  - Walking slowly: 5,000,000
  - Exercise: 10,000,000
  - Physical exercises: 25,000,000

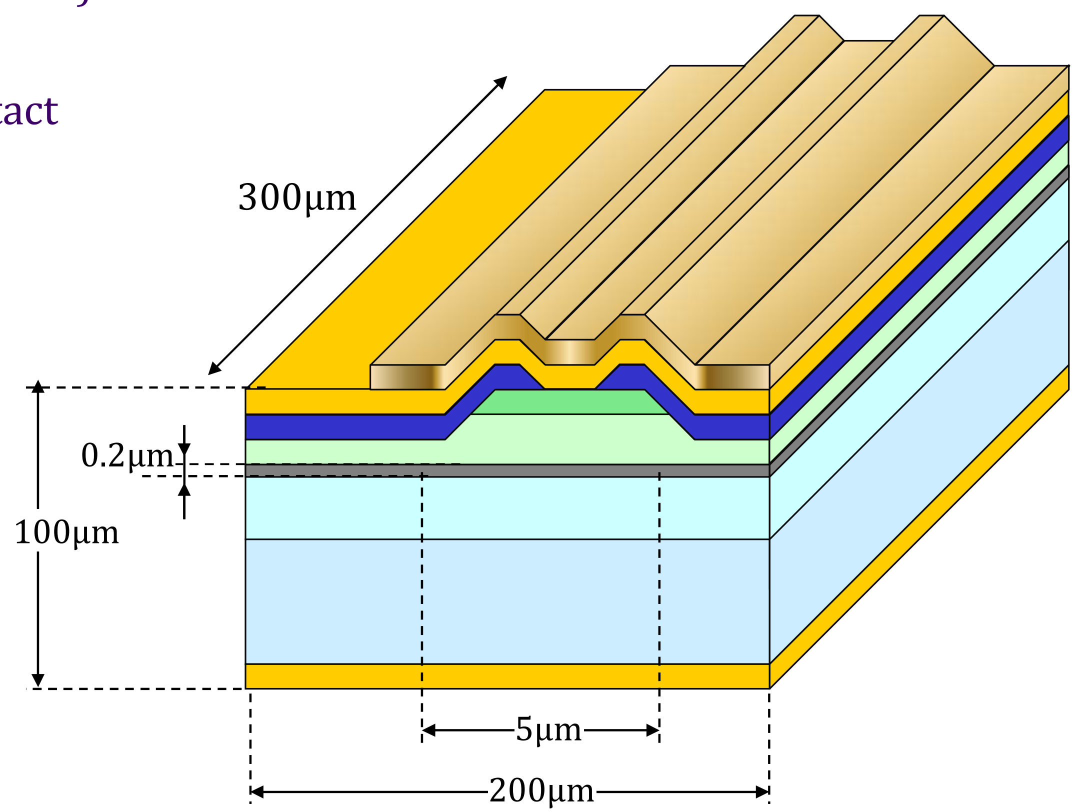
Clean Room Architecture

- Air circulation:
  - from the top to the bottom
  - as small turbulence as possible
  - clean room pressure is higher than the outside



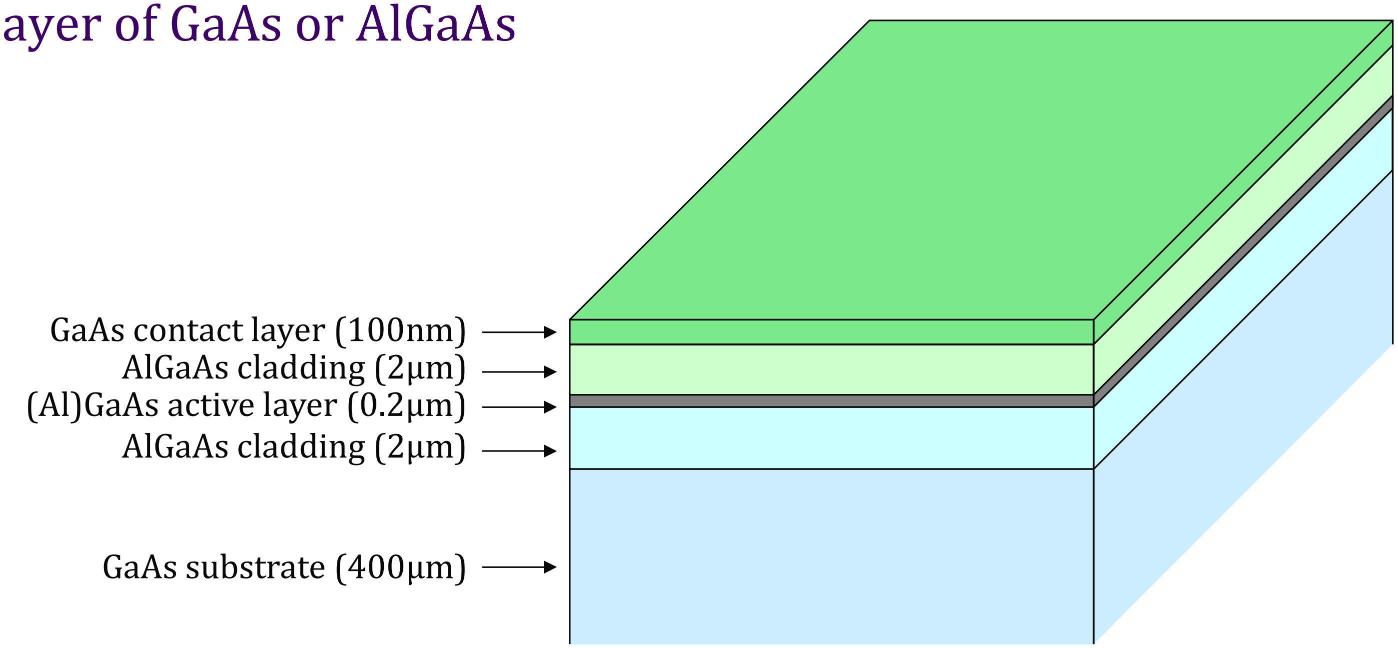
Stripe laser diode

- Fabrication
  - Definition of the stripe (mesa)
  - Isolation layer deposited
  - Metallization for top contact
  - Thinning
  - Bottom contact



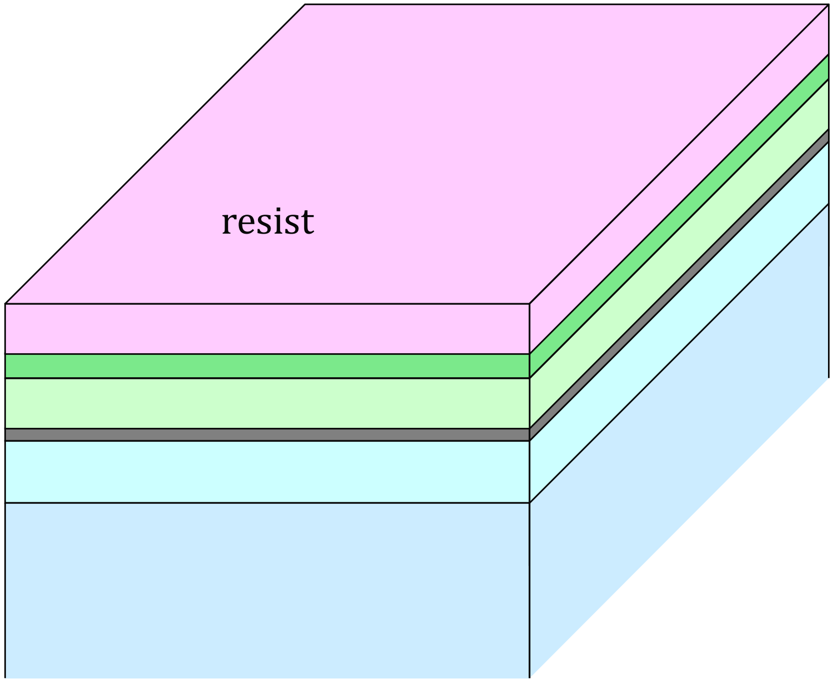
Fabrication of the laser diode (1)

- Layer structure
  - GaAs carrier
  - AlGaAs coating on the top and at the bottom
  - Active layer of GaAs or AlGaAs



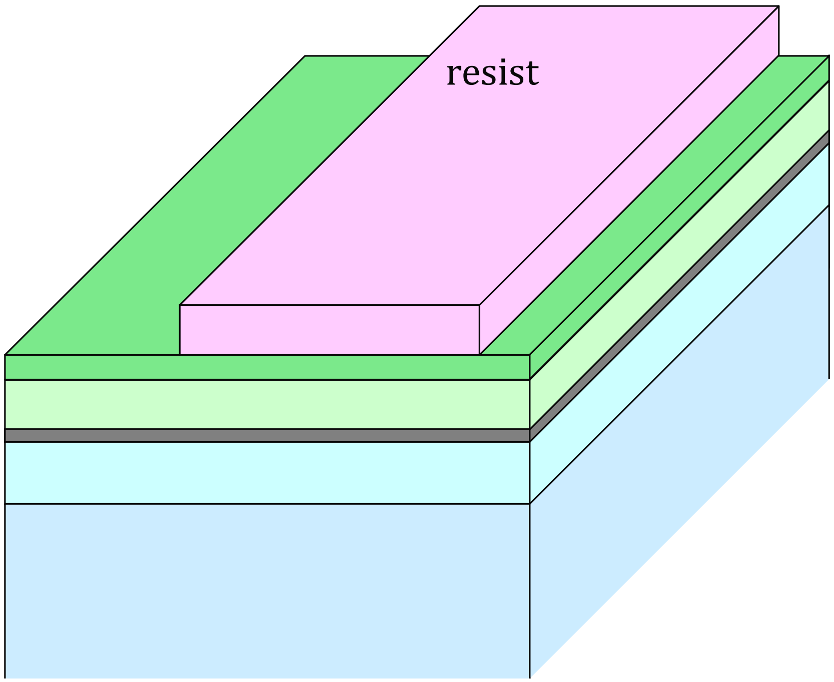
Fabrication of the laser diode (2)

- Definition of the mesa
  - Spin coating



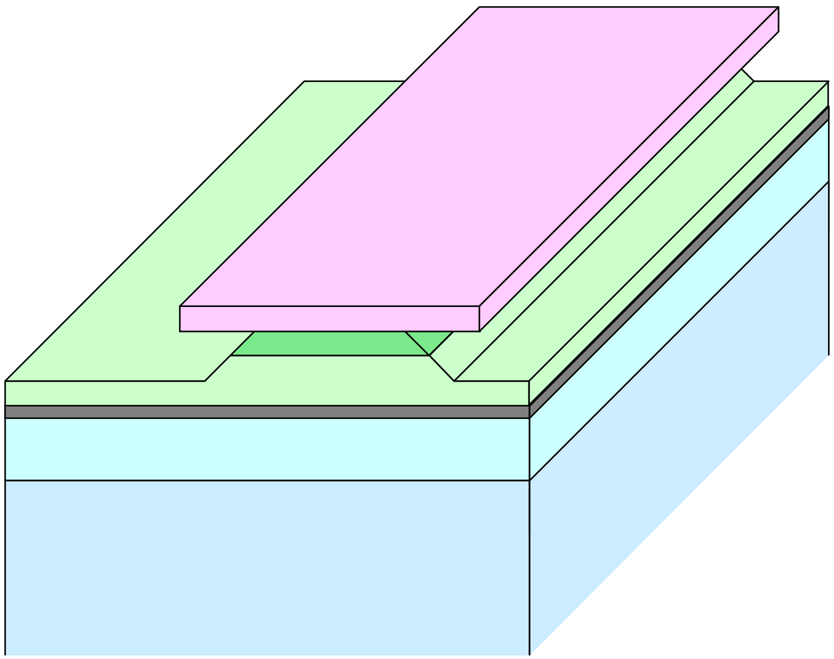
Fabrication of the laser diode (3)

- Definition of the mesa
  - Spin coating
  - Photolithography



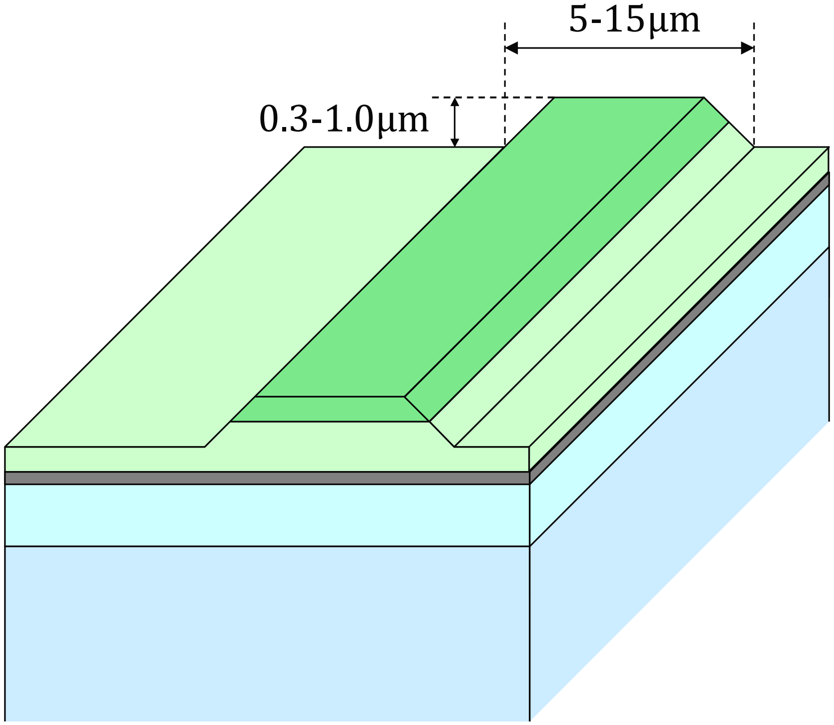
Fabrication of the laser diode (4)

- Definition of the mesa
  - Spin coating
  - Photolithography
  - Wet etching



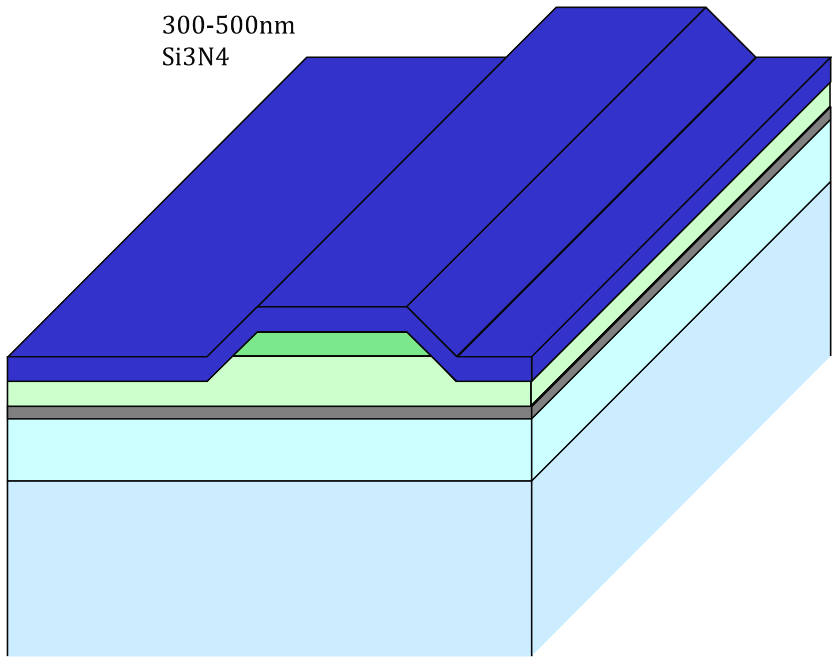
Fabrication of the laser diode (5)

- Definition of the mesa
  - Spin coating
  - Photolithography
  - Wet etching
  - Resist removal



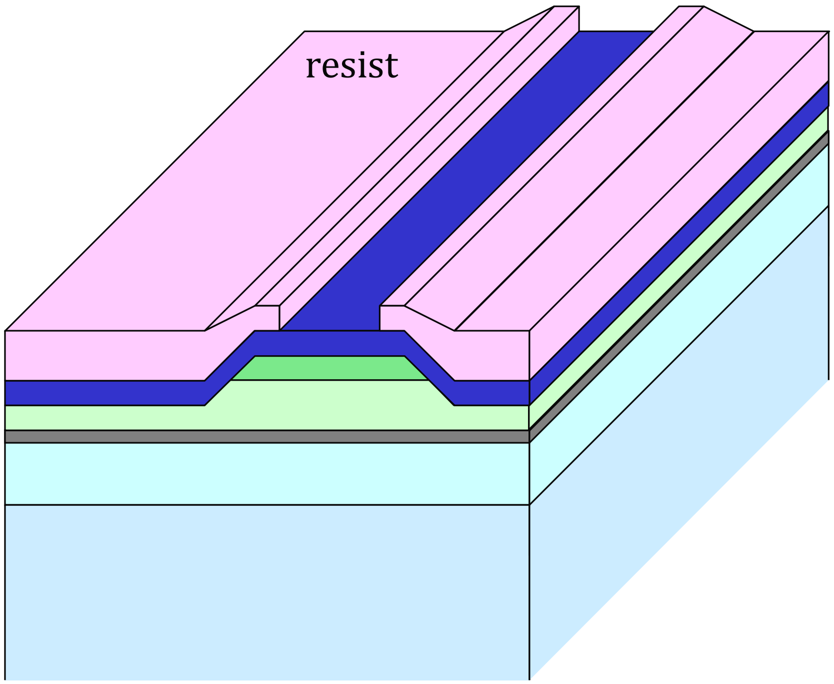
Fabrication of the laser diode (6)

- Definition of the mesa
- Nitride isolation layer
  - Deposition of Si_3N_4



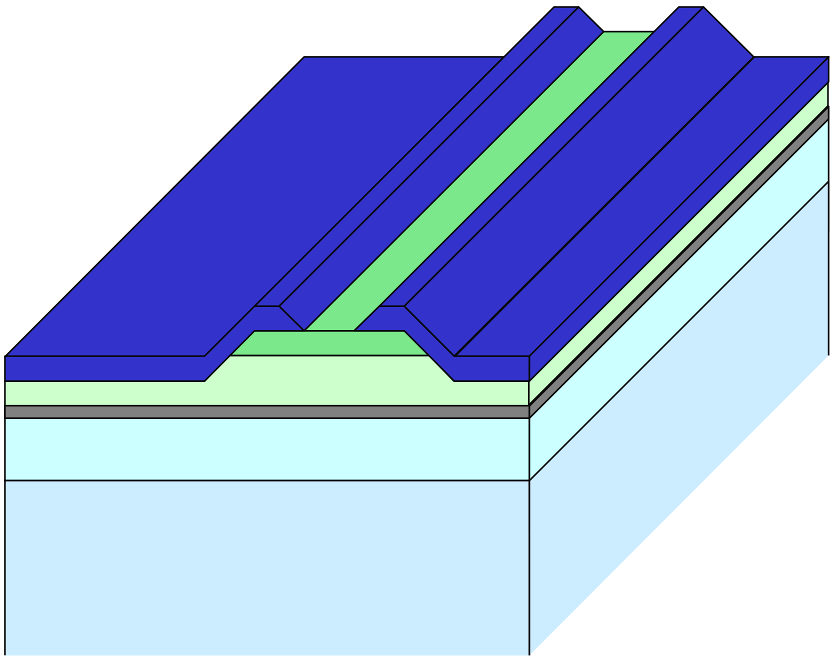
Fabrication of the laser diode (7)

- Definition of the mesa
- Nitride isolation layer
  - Deposition
  - Photolithography



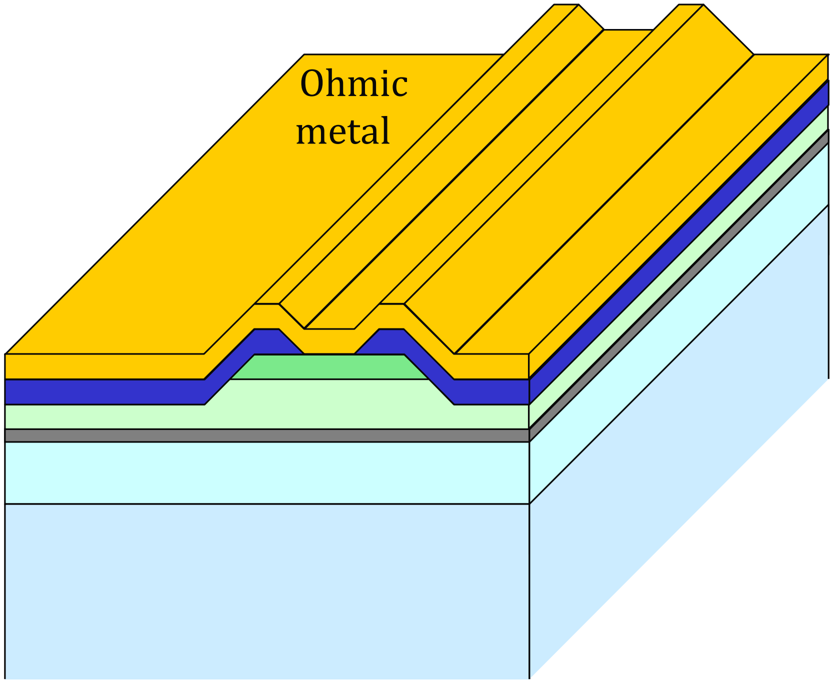
Fabrication of the laser diode (8)

- Definition of the mesa
- Nitride isolation layer
  - Deposition
  - Photolithography
  - Dry etching



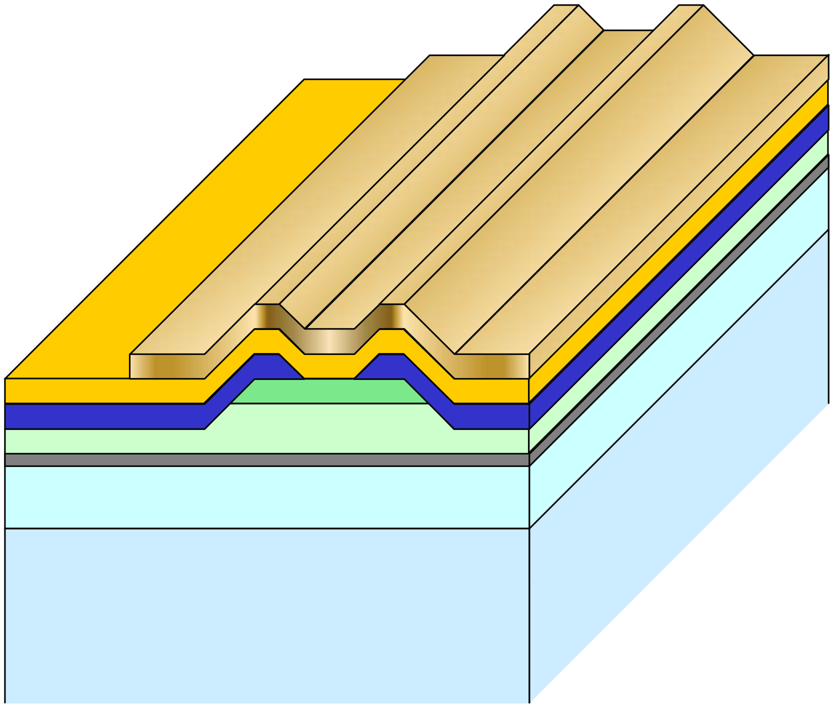
Fabrication of the laser diode (9)

- Definition of the mesa
- Nitride isolation layer
- Top contact
  - Deposition of Ohmic contact



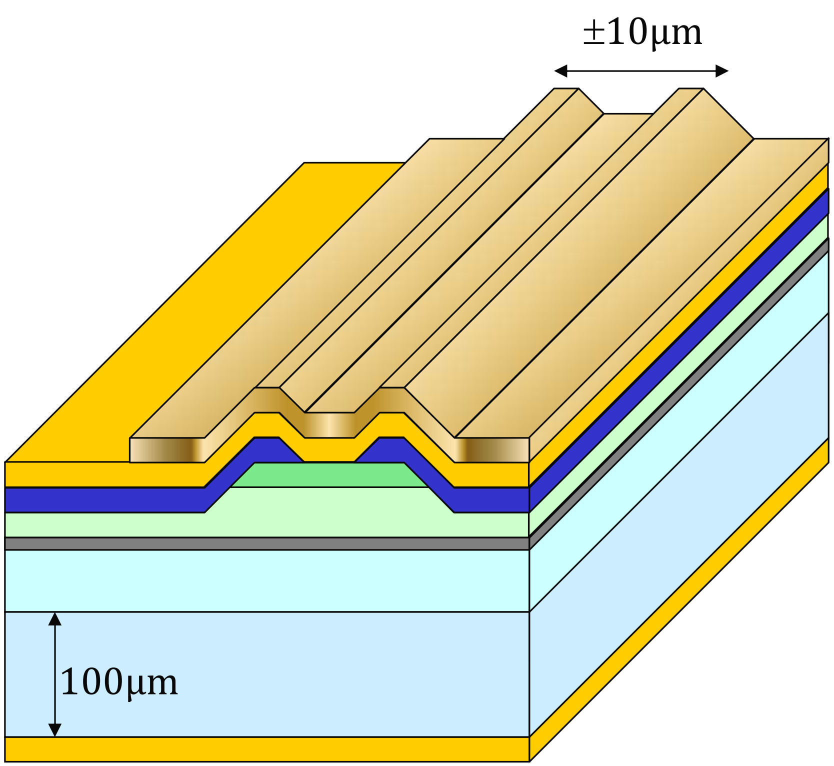
Fabrication of the laser diode (10)

- Definition of the mesa
- Nitride isolation layer
- Top contact
  - Deposition of Ohmic contact
  - Gold layer deposition
  - Lithography
  - Lift-off or etching



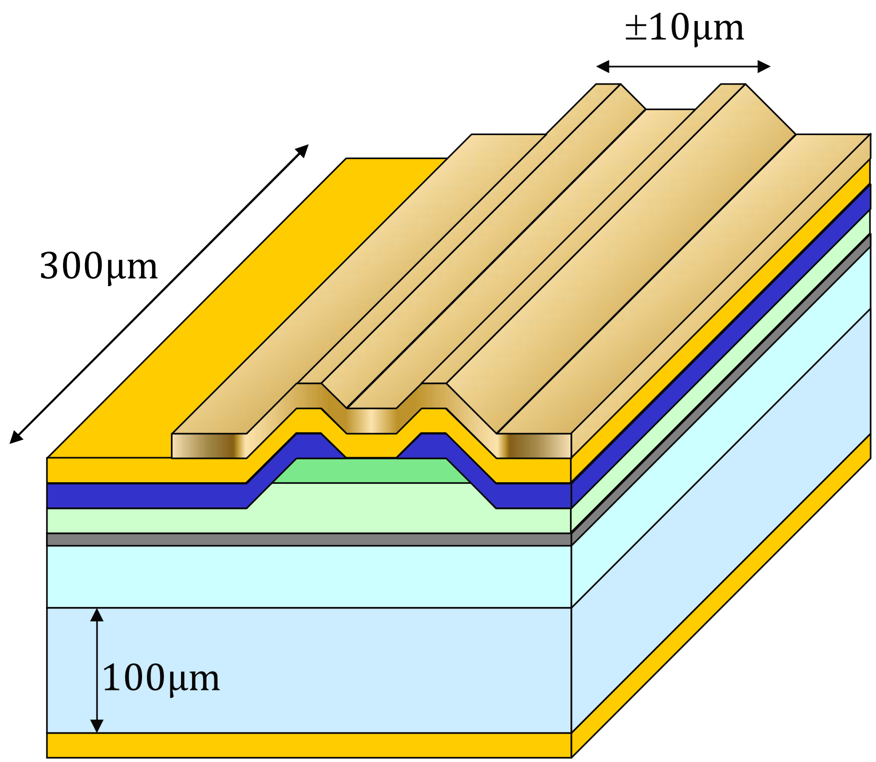
Fabrication of the laser diode (11)

- Definition of the mesa
- Nitride isolation layer
- Top contact
- Bottom contact
  - Substrate thinning
  - Deposition of metal



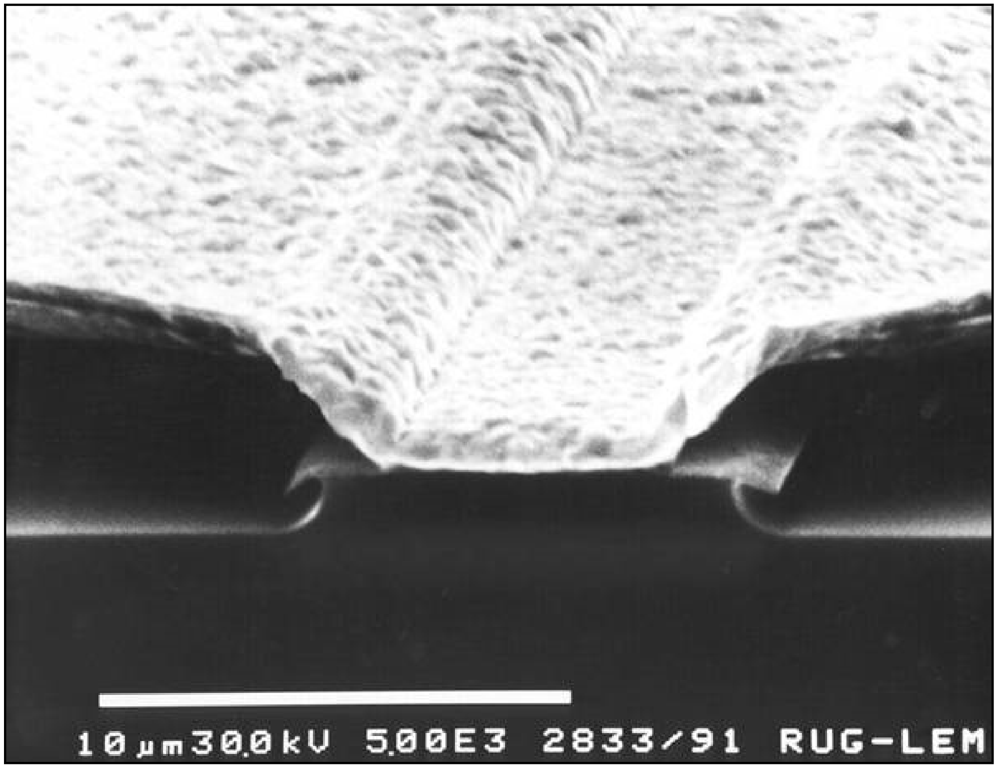
Fabrication of the laser diode (12)

- Definition of the mesa
- Nitride isolation layer
- Top contact
- Bottom contact
- Cleaving of facets



Laser diode

- InGaAs/AlGaAs laser diode (wavelength = 980nm)
  (isolation layer is etched away from under the metal by wet etching)



Stripe laser diode

- Laser array for interconnects